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ABSTRACT

This is one of five panel reports that have been prepared as part of the first phase of Project 2061, a long-term, multipurpose undertaking of the American Association for the Advancement of Science designed to help reform science, mathematics, and technology education in the United States. Major sections included are: (1) "Introduction" (describing the nature of physical science, information science, and engineering); (2) "Social Interactions"; (3) "Methods"; (4) "Models and Measurement"; (5) "Unifying Concepts" (including the concepts of materials, energy, information, and systems); (6) "Key Specific Concepts" (providing concepts in the area of physics and chemistry, earth and astronomical sciences, information science and computer science, and engineering); and (7) "Notes on Learning" (suggesting ideas on teaching). The members of the panel and consultants are listed. (YP)

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PHYSICAL AND INFORMATION SCIENCES AND ENGINEERING

SE 050 109

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

PHYSICAL AND INFORMATION SCIENCES AND ENGINEERING

REPORT OF THE
PROJECT 2061 PHASE I
PHYSICAL AND INFORMATION
SCIENCES AND ENGINEERING
PANEL

by George Bugliarello

AMERICAN ASSOCIATION
FOR THE ADVANCEMENT OF SCIENCE

1989

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Founded in 1848, the American Association for the Advancement of Science is the world's leading general scientific society, with more than 132,000 individual members and nearly 300 affiliated scientific and engineering societies and academies of science. The AAAS engages in a variety of activities to advance science and human progress. To help meet these goals, the AAAS has a diversified agenda of programs bearing on science and technology policy; the responsibilities and human rights of scientists; intergovernmental relations in science; the public's understanding of science; science education; international cooperation in science and engineering; and opportunities in science and engineering for women, minorities, and people with disabilities. The AAAS also publishes *Science*, a weekly journal for professionals, and *Science Books & Films*, a review magazine for schools and libraries.

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On behalf of the Board of Directors of the American Association for the Advancement of Science, I wish to acknowledge with gratitude the many useful contributions made by the members of the Phase I Physical and Information Sciences and Engineering Panel to the first stage of Project 2061.

The nine panel members were most generous with their time and efforts over a two-year period in developing their response—as presented in this report—to the complex question of what young people should know about the physical and information sciences and engineering by the time they complete their high school education. The board is also very grateful to George Bugliarello, who chaired the panel and also wrote the panel's report.

During this essential first stage of Project 2061, the Physical and Information Sciences and Engineering Panel was one of five scientific panels charged by the AAAS with developing independent reports on five basic subject-matter areas. At the same time, the Project 2061 staff—in conjunction with the National Council on Science and Technology Education—was preparing a separate overview report—*Science for All Americans*—that was able to draw on the conclusions reached by the individual panels.

We also want to add our thanks to those of George Bugliarello to the many people who assisted the Physical and Information Sciences and Engineering Panel in the course of the panel's deliberations—the consultants, the national council members and other reviewers, and the Project 2061 staff.

Finally, it is appropriate to note that Project 2061 is indebted to the Carnegie Corporation of New York and the Andrew W. Mellon Foundation for their overall and ongoing support of our various Phase I efforts.

Sheila E. Widnall
Chair, Board of Directors, American Association for the Advancement of Science

PHASE I PHYSICAL AND INFORMATION SCIENCES AND ENGINEERING PANEL

George Bugliarello (Panel Chair) President, Polytechnic University

James J. Conti Vice President for Educational Development, Polytechnic University

David H. Copp Member of the Technology Staff, Bell Communications Research

Kathleen Crane Associate Professor of Geology, Hunter College, City University of New York

Samuel Devons Professor Emeritus of Physics, Nevis Laboratories, Columbia University

Paul Garabedian Professor of Mathematics, Courant Institute of Mathematical Sciences, New York University

William Starnes Professor of Chemistry, Polytechnic University

Alan Strahler Professor of Geography, Boston University

Spencer Weart Director, Center for History of Physics, American Institute of Physics

Panel Staff: Margaret Mastrianni, Executive Assistant to the President, Polytechnic University

FOREWORD

This report is one of five prepared by scientific panels as part of Phase I of Project 2061. Each of the panel reports stands alone as an independent statement of learning goals in a particular domain. In addition, the reports contributed to *Science for All Americans*, a Phase I report that cuts across all of science, mathematics, and technology.

The work of the Physical and Information Sciences and Engineering Panel was to reflect on all aspects of the panel's subject areas—their nature, principles, history, future directions, social dimensions, and relation to the other sciences—and to produce a set of recommendations on what knowledge and skills are needed for literacy in these areas (as part of general scientific literacy). The other panels focused in a similar way on the biological and health sciences, mathematics, the social and behavioral sciences, and technology.

In considering this report, it is helpful to see it in the context of Project 2061 and to be aware of the manner in which it was generated.

The American Association for the Advancement of Science initiated Project 2061 in 1985, a year when Comet Halley happened to be in the earth's vicinity. That coincidence prompted the project's name, for it was realized that the children who would live to see the return of the comet in 2061 would soon be starting their school years. The project was motivated by a concern that many share for the inadequate education those young Americans will receive unless there are major reforms in science, mathematics, and technology education.

Scientific literacy—which embraces science, mathematics, and technology—has emerged as a central goal of education. Yet the fact is that general scientific literacy eludes us in the United States. A cascade of recent studies has made it abundantly clear that by national standards and world norms, U.S. education is failing too many students—and hence the nation. The nation has yet to act decisively enough in preparing young people—especially the minority children on whom the nation's future is coming to depend—for a world that continues to change radically in response to the rapid growth of scientific knowledge and technological power.

Believing that America has no more urgent priority than the reform of education in science, mathematics, and technology, the AAAS has committed itself, through Project 2061 and other activities, to helping the nation achieve significant and lasting educational change. Because the work of Project 2061 is expected to last a decade or longer, it has been organized into three phases.

Phase I of the project has established a conceptual base for reform by defining the knowledge, skills, and attitudes all students should acquire as a consequence of their total school experience from kindergarten through high school. That conceptual base consists of recommendations presented in *Science for All Americans* and the five panel reports.

In Phase II of Project 2061, now under way, teams of educators and scientists are transforming these reports into blueprints for action. The main purpose of the second phase of the project is to produce a variety of alternative curriculum models that school districts and states can use as they undertake to reform the teaching of science, mathematics, and technology. Phase II will also specify the characteristics of reforms needed in other areas to make it possible for the new curricula to work: teacher education, testing policies and practices, new materials and modern technologies, the organization of schooling, state and local policies, and research.

In Phase III, the project will collaborate with scientific societies, educational associations and institutions, and other groups involved in the reform of science, mathematics, and technology education, in a nationwide effort to turn the Phase II blueprints into educational practice.

Each of the five panels was composed of 8 to 10 scientists, mathematicians, engineers, physicians, and others known to be accomplished in their fields and disciplines and to be fully conversant with the role of science, mathematics, and technology in the lives of people. The panelists were different from one another in many respects, including their areas of specialization, institutional affiliations, views of science and education, and personal characteristics. What made it possible to capitalize on the rich diversity among the panelists was what they had in common—open minds and a willingness to explore deeply the questions put to them.

The basic question put to the Physical and Information Sciences and Engineering Panel was: What is the physical and information sciences and engineering component of scientific literacy? Answering this question—difficult enough in itself—was made more difficult by the conditions, or ground rules, set by Project 2061. Abbreviated here, these were:

- ***Focus on scientific significance.*** Identify only those concepts and skills that are of surpassing scientific importance—those that can serve as a foundation for a lifetime of individual growth.

- ***Apply considerations of human significance.*** Of the knowledge and skills that meet the criterion of scientific significance, select those that are most likely to prepare students to live interesting and responsible lives. Individual growth and satisfaction need to be considered, as well as the needs of a democratic society in a competitive world.

- ***Begin with a clean slate.*** Justify all recommendations without regard to the content of today's curricula, textbooks, state and school district requirements, achievement tests, or college entrance examinations.

- ***Ignore the limitations of present-day education.*** Assume that it will be possible to do whatever it may take—design new curricula and learning materials, prepare teachers, reorganize the schools, set policies, or locate resources—to achieve desired learning outcomes.

- *Identify only a small core of essential knowledge and skills.* Do not call on the schools to cover more and more material, but instead recommend a set of learning goals that will allow them to concentrate on teaching less and on doing it better.

- *Keep in mind the target population—all students.* Propose a common core of learning in the physical and information sciences and engineering that can serve as part of the educational foundation of all students, regardless of sex, race, academic talent, or life goals.

Taking these ground rules into account, the members of the Physical and Information Sciences and Engineering Panel met frequently over a period of nearly two years to present and debate ideas and to consider the suggestions of consultants. The panel members prepared working papers and revised them in response to the criticisms of reviewers. This process—which also included meetings with the chairs of other panels—led to the preparation of this report.

The task ahead for the United States is to build a new system of education that will ensure that all of our young people become literate in science, mathematics, and technology. The job will not be achieved easily or quickly, and no report or set of reports can alter that. I believe, however, that this report on literacy in the physical and information sciences and engineering, along with the other panel reports and *Science for All Americans*, can help clarify the goals of elementary and secondary education and in that way contribute significantly to the reform movement.

F. James Rutherford
Project Director, Project 2061

PREFACE

The panel's assignment for the first phase of Project 2061 was to identify key concepts in the physical and information sciences and in engineering that—in our opinion—a high school graduate should know. Given that the task of the next phase of the project is to design school curricula, the goal of our report has been to identify key concepts that will help our educators to teach and our students to learn about the physical and information sciences and engineering.

We hope that by understanding nature, students will acquire a sense of belonging in the universe—a sense of roots—and that by understanding how we can modify nature, they will gain a sense of the options people have for controlling technology and the future. We further hope that students, by developing an understanding of a scientific truth as a verifiable truth (but not an immutable one, as new facts or understandings may supersede it) and by learning what the process of verification entails, will acquire one of the most powerful tools that a human being can possess to survive and thrive in the universe. We also hope that students will view the physical and information sciences and engineering as interrelated activities, which in turn influence and are influenced by all other human activities.

We are most grateful to the many people who have provided us with helpful suggestions in the preparation of this report. These people range from the members of the Project 2061 National Council on Science and Technology Education to the Project 2061 staff to the members of Section T (Information, Computing, and Communication) of the American Association for the Advancement of Science. Special thanks go to Anna J. Harrison of Mount Holyoke College and past president of AAAS; E. Margaret Burbidge of the University of California, San Diego; Donald F. Holcomb of Cornell University; and Charles R. Tolbert of the University of Virginia for their thoughtful and constructive review of drafts of this report. We also would like to acknowledge the assistance of Gloria Kaplan and Roberta Baltin, both formerly on the staff of Polytechnic University. Sad to say, Marvin P. Epstein, a consultant to the panel and a very significant contributor to its deliberations, passed away between the time this report was written and the time it went to press.

George Bugliarello
Chair, Physical and Information Sciences and Engineering

SECTION 1

INTRODUCTION

The creativity of science and engineering lies in combining the evidence of the senses with the reasoning and the imagination of the mind. Thus, in "doing science" or being introduced to simple engineering concepts, students need to learn to observe and make measurements and to construct abstractions, or models, of phenomena.

The theories of the physical and information sciences and the designs of engineering are often conveniently expressed in mathematical form, even if their initial formulation may be in words (hence, the importance of precise language) or depicted graphically. Mathematics is used to describe such laws, principles, or phenomena as the conservation of energy, electromagnetic radiation, or the transmission of information, and to formulate models of physical reality and of engineering artifacts. Newton's calculus plays a key role in the physical and engineering sciences. Thus, we believe that as much as possible, the sciences and engineering should be learned in schools in conjunction with mathematics.

Just as important as the curriculum content (if not more so) is the context in which it is taught. Thus, it is particularly fruitful and appropriate to stress the relevance of the physical and information sciences and engineering to everyday human experience, the other sciences, the arts, and the humanities. That relevance can best be addressed by using an integrated pedagogical approach that examines phenomena from several perspectives simultaneously, rather than from the compartmentalized perspectives traditionally adopted by different disciplines. Nevertheless, compartmentalized perspectives should not be obliterated, because there are basic concepts intrinsic to specific sciences, such as chemistry, that need to be understood by all high school graduates (for example, how the properties of atoms and molecules contribute to reality as a whole).

The physical and information sciences and engineering focus on nature, albeit with different intent, and are synergistic. We can alter nature rationally only by understanding it, and to understand it, we need instruments and other artifacts. Hence, it is logical in this report to consider the physical and information sciences together with engineering.

THE PHYSICAL SCIENCES

The fundamental physical science, physics, is concerned with the development of the most basic concepts with which we can understand nature—from nature's smallest subatomic components to its largest manifestation, the universe. These concepts, and the "laws" through which we seek to express and interconnect them, are the underpinning of all the other sciences.

As aggregates of increasing scale and complexity are formed from the smallest components of nature, they manifest new

characteristics. Thus, science cannot be reduced to just the study of the smallest components of nature, although the properties of such components are embodied in the larger-scale phenomena.

The immense variety of nature's manifestations has led to specialization in science. It has led to distinguishing between the physical sciences—the sciences dealing primarily with inanimate phenomena—and the life sciences, as well as to distinguishing between several aspects of the physical sciences. These aspects are encompassed by a variety of disciplines ranging from physics to chemistry, the earth sciences, astronomy, and oceanography.

Specializations, however, are a matter of convenience. Nature is one, and its manifestations do not fall neatly into our categories. Nature's manifestations generally involve aspects of all such categories, and they often require entirely new viewpoints. Thus, as we learn more about nature, we constantly need to take a fresh look at how we categorize it for the purpose of studying it. Even if we find it expedient to preserve the distinctions between disciplines, we must recognize and foster the interactions among them.

THE INFORMATION SCIENCES: INFORMATION SCIENCE AND COMPUTER SCIENCE

In the broadest sense, the information sciences are pertinent to all forms of human knowledge and expression. More specifically, information science deals with the patterns we generate in our minds to extract meaning (information) from the world around us and in us, and to convey that meaning to other human beings, as well as (increasingly) to machines. Thus, information science addresses the nature, manipulation, and communication of information. In the technological domain, it provides the foundation for the development of computers and of computer science, which—most generally—deals with the study of computation, whether performed by humans or by machines. In turn, the development of computer science spurs that of information science. Information science and computer science, therefore, have a fundamental relationship to one another, but they are not the same. We can include them both under the term "information sciences."

The information sciences deal with the human interpretation of nature—how our minds operate in perceiving the world around us and in abstracting features that may be of use to us. The information sciences draw from physical and biological sciences, as well as from mathematics and philosophy; they have, in turn, applications in all of those fields, in the social sciences, and in virtually any other activity of a technological society such as ours. Linguistics is a central subdiscipline, and communications and library science are particular aspects of information sciences.

Information science and computer science have both theoretical and practical components. Information theory, computability, and complexity theory are strongly rooted in modern mathematics. Computer programs, communication systems, and information-retrieval systems are building blocks of technological society. The modern world is filled with computers and information

systems. Consequently, the notion of basic literacy needs to be expanded beyond reading and writing and the use of conventional libraries to include the use of modern information systems (including archives and data banks) and of simple computer-based tools for handling information and performing logical tasks.

ENGINEERING

Throughout their history, humans not only have endeavored to understand nature but also have felt the need to modify it—by the creation of artifacts for strictly utilitarian purposes (shelters, prostheses, weapons, dams, etc.), religious purposes (cathedrals, tombs, etc.), and aesthetic or other purposes. The ability to modify nature is not unique to humans among living species, but in them it has gone beyond instinct, thereby sharply differentiating us from other living species.

Of the many approaches humans can use to modify nature, engineering as a rational process involving planned design and execution of artifacts goes back to the beginning of civilization, as exemplified by the pyramids, early ships, the working of metals, and the building of canals. In the last two centuries, engineering (in the modern sense of the word) has emerged as a discipline characterized by a powerful combination of logic, experience, and science. It is the core discipline of that complex social activity or process called technology, which produces and operates artifacts and provides services.[1]

Historically, engineering has focused primarily on nonliving systems. Recently, however, bioengineering has been bringing engineering to bear on living systems as well: The new thrusts in genetic engineering are in effect a redesigning of living systems.[2] As in the case of the physical sciences, the great variety of ways in which we can modify nature, and the myriad artifacts that we can create, have led engineering to develop distinct branches, such as those associated with the building of structures (bridges, buildings, highways), transportation (aircraft, ships, automobiles), electrical devices (computers, electric motors, power lines), chemical transformations of matter (metal working, refineries, chemical reactors), and power generation (thermal plants, nuclear reactors, internal combustion engines). There are also branches of engineering exclusively involved with processes—branches such as manufacturing engineering, industrial engineering (the optimization of industrial and other processes), and agricultural engineering.

[1] To clarify the relation between this Project 2061 report and the complementary report on technology, it may be useful to view engineering as bearing a relation to technology somewhat analogous to that of medicine to health care.

[2] The fact that they are carried out by persons labeled "scientists" serves to underscore that the activities labeled "science" and "engineering," although conceptually quite distinct, are also complementary. Scientists often engage in engineering—in the modification of nature—and engineers engage in science—in the learning about nature.

SECTION 2

SOCIAL INTERACTIONS

The physical sciences, information sciences, and engineering have powerful effects on all aspects of our society and our lives. Insofar as the physical sciences provide us with an understanding of nature (and the information sciences help us in extracting meaning from nature and in ordering, storing, and conveying our experience), these sciences lead us to redefine our relationship to the world around us and our understanding of ourselves. Thus, with Copernicus and Galileo, the recognition of the fact that the earth revolved around the sun—rather than vice versa—changed the view of humans being the center and purpose of the universe.

In turn, the understanding provided by engineering of how to modify nature and create artifacts is crucial to the educated citizens of the future; they will live in increasingly technological—that is, human-made—environments. Employment, health, leisure, values, and political decisions will all be profoundly affected by the work of the engineer. Furthermore, given that science and engineering provide us with ever more powerful understandings of nature and ever more powerful tools for altering it and creating artifacts, we must learn how to intelligently question the wisdom, direction, and extent of our interventions in nature. We must also learn to reflect on the impact that our artifacts are having on our lives and our humanity. Thus, school curricula need to convey an understanding of the nature, method, and consequences of engineering as an activity distinct from science, but yet closely intertwined with it.

Not only does the character of our present civilization depend on knowledge of the physical and information sciences and engineering, but the very history of our civilization has interacted intimately with the growth of this knowledge. The breakthrough of Galileo would not have been possible without the way having been paved by the Renaissance (which reestablished and perfected, 2,000 years after it had been introduced by the ancient Greeks, a new form of inquiry free from dogma). Similarly, the Industrial Revolution would not have been possible without the steam engine—nor the postindustrial society without information theory and the computer. Accordingly, our schools need to emphasize the points of contact and interaction among the physical and information sciences, the other sciences, engineering, the arts, and the humanities, as representing the essence of a modern general education.

Many impacts of the physical sciences and information sciences and of engineering on the ways in which we make a living or wage war are so obvious as not to warrant further mention here. There are some other impacts, however, that deserve to be considered. For example, science and engineering, by providing us with new tools and new concepts, have led to the creation of new forms of art, from photography to Pointillism, from electronic music to computer imaging; new forms of leisure, from watching television to transoceanic tourism, from ballooning to wind surf-

ing; new aesthetic canons, from functionalism in architecture (the Brooklyn Bridge and the Eiffel Tower) to abstraction in painting; a new emphasis in philosophical discourse, from linguistics to artificial intelligence; new forms of scholarly inquiry, from printing to the ability (thanks to computers and information sciences) to assemble and analyze vast amounts of knowledge; and new forms of journalism, from the televised shooting of Lee Harvey Oswald to the televised viewing of distant societies.

Furthermore, telecommunications has brought into many homes such activities such as football, drama, and religion. Artists have not hesitated to experiment with new materials, such as plastics; and many a contemporary novel—as a literary portrait of the human condition—reflects the influence of technology. Technology has brought forth a heightened sense of materialism, and it has also stimulated conflict between convenience and creativity in such forms of self-expression as the culinary arts. Through travel and telecommunications, intercultural differences have been bridged, and a widespread sense has been developed of the physical and social connectedness of the world—of the "Spaceship Earth."

Here are some further points of interaction of the physical and information sciences, engineering, the humanities, and social sciences (by way of example and in random order):

- Chemistry has contributed to the preservation and restoration of paintings and sculptures. The chemical composition of paints has a major impact on art. The longevity of book paper depends greatly upon the chemistry of the process by which the paper is made, as well as upon the temperature and humidity at which it is stored.

- A mountain can be viewed as an object of scientific observation or poetic contemplation, or as a symbol of a deity.

- There are fundamental limits on information processing. For instance, the speed of light limits the rate at which we can communicate and compute—which is one of the factors in the design and operation of unmanned space probes.

- Engineering affects the way people eat, breathe, work, play, move, communicate, dress, and think. Engineering enables individuals to have more time to relax and to enjoy interacting with some of the available technological artifacts, such as a car or a television set. At the same time, the development of engineering has led to public concern about the potentially negative consequences brought forth by artifacts, such as radiation, air pollution, or psychological stress. In the Western world, that concern has taken the form of a flight from technology, at least in its more organized and advanced forms (for example, the return of some people to simpler agrarian communities) and of a concomitant rebellion against materialism (which is viewed as the inevitable product of technology).

- Mass production has been made possible by standardization, an important engineering concept. Standardization has in turn led to depersonalization. But is this inevitably so? Is mass production necessarily inconsistent with individuality?

SECTION 3

METHODS

Doing science is a complicated process, which, in its purest terms, includes observing phenomena; questioning why they occur (for example, why is there wind?); developing hypotheses as to how the phenomena come about; designing and executing experiments to test the hypotheses and study phenomena further; and refining the conclusions to conform with observations. Verification is the essential characteristic that distinguishes science from other human ways of knowing, such as poetry or religion, in the sense that a statement is scientifically valid only if it can be verified objectively. Sets of conclusions that address a considerable body of phenomena become embodied in theories, which remain valid until disproved by new observations or new insights. This ability to observe, analyze, predict, and verify is highly functional in our society, being used for everyday problems ranging from dealing with a stalled automobile to deciding on whether to ban nuclear power. Searching for cause and effect, identifying critical factors, making measurements and collecting data—skills that are all part of doing science—directly enhance an individual's value to society and the quality of an individual's life or power over his or her own situation. Consequently, getting students to learn to do science must be a key goal of U.S. science education, for they need to be able to think and probe independently. Ultimately, in terms of the survival and progress of society, such an ability may be far more important than an understanding of specific scientific concepts, however fundamental they may be.

"Doing engineering" is also a complicated process, with many elements in common with the process of doing science: observation, hypotheses, theories, testing, and verification. The fundamental difference is one of intent: Whereas the sciences endeavor to understand, engineering endeavors to utilize, modify, and manipulate, using the understanding of the sciences. At times, engineering moves ahead of the sciences; for example, cannons were fired before there was an understanding of ballistic theory, bridges were built before there was a science of the strength of materials, and Marconi produced radio waves that crossed the Atlantic Ocean before a theory was developed to explain their reflection by the ionosphere.

At the core of engineering is the concept of design—the scheme or process by which nature is to be manipulated and artifacts are to be created and made to function. In the earlier phases of engineering, design made heavy use of trial and error, serendipity, and empiricism. As the body of empirical knowledge increased and the application of science to explain the behavior of systems also increased, the methodology of engineering became more scientific, acquiring ever-increasing sophistication.

SECTION 4

MODELS AND MEASUREMENT

Models can assume many forms. They can be, for instance, *verbal* descriptions of a phenomenon, principle, or design, or they can be *graphical*, *physical* (scaled up or down), *analogical*, or *mathematical* representations. Thus, a bridge could be described in words (for instance, "a road over a gap"), drawn on paper, or represented on a small scale by a board between two supports. The traffic over the bridge could be described by analogy to an electric current, and the stresses under load could be described mathematically.

Models are tools for thinking. A particularly important set of models consists of those that use order-of-magnitude considerations and dimensional analyses. For instance, why do raindrops have a given size? How many raindrops hit the United States on a given day? Why does it take a few hours, rather than minutes or days, to digest a meal? What is the difference between the stomach and a furnace? It is far better if students learn to use order-of-magnitude considerations to address such questions than if they simply memorize facts; for example, they should develop a sense of what digestion is rather than just knowing the location of the gall bladder, or what lipase or pepsin is. Nevertheless, many facts are critical to effective learning; therefore, an intelligent balance must be struck between facts and models.

SECTION 5

UNIFYING CONCEPTS

The task of teaching the physical and information sciences and engineering in the elementary and secondary schools can be facilitated by focusing on concepts that are common to all aspects of the subjects and often may be useful in the life sciences and the social sciences. Indeed, as an alternative to the traditional disciplinary approach, one can envision teaching all the sciences as well as engineering in an interdisciplinary fashion, by teaching a set of unifying concepts and their meaning in the various traditional disciplines.

What may be most useful unifying concepts is to a considerable extent a matter of choice. Here, we suggest four key concepts, complemented by a number of other general concepts that often cut across them. It is our hope that these key and general concepts will be taken only as examples, and that our suggesting them will not be viewed as advocacy of a new orthodoxy.

KEY UNIFYING CONCEPTS

The four key unifying concepts we suggest by way of example are those of materials, energy, information, and systems. They are all strongly interrelated. For example, there is no material without energy (bonding energies, nuclear energy, etc.); energy is needed to modify materials; information is needed to know how to manipulate and save materials and energy; a system requires the exchange of information among its components, and often of materials or energy as well.

Within each of these four concepts, we can focus on some aspects of general interdisciplinary utility. The depth to which this is done should be left to the teacher. The essential point is that it is possible to introduce the unifying concepts at any desirable level of complexity, according to the grade and skills of the student, and that even in their simplest formulation, such concepts provide us with useful and powerful tools to understand the world around us—be it natural or human-made.

The Concept of Materials

Under the concept of materials, one could include the following topics:

- The definition of materials, and their various manifestations (solids and fluids [both liquids and gases]) and uses.

- The properties of materials (for example, density, heat capacity, thermal conductivity, and atomic number, as well as properties that impart strength, cohesion, fluidity, or transparency) and their role in both how we understand nature and how we modify it (for example, by creating new materials with new properties).

- The conservation of materials, unless transformed into energy (for example, we cannot really get rid of waste, the key factor in the environmental damage wreaked by consumer-oriented and heavily populated societies).

- The transformations from material to material and from material to energy, or vice versa (a process involving an understanding of the atomic and molecular structure considered in physics and chemistry).

The Concept of Energy

The following topics could be included under the concept of energy:

- The definition of energy and its various manifestations (heat, gravitational, bonding, electromagnetic, etc.) and uses.

- Fields, gradients, and potentials (for example, why we slide downhill and why we get an electric shock).

- The conservation of energy, including mass as an equivalent form of energy (mass is energy).

- The transformations among various forms of energy (again, to be related to atomic and molecular structure); and the conversion between rest mass and kinetic energy (with the total mass—that is, energy—remaining constant).

- Energy transfer (for example, heat transfer), degradation, and entropy.

- Efficiency and its theoretical and practical limits.

As an example of the use of a unifying concept, we can follow the transformation of a given amount of energy that originates in a given form. One example might be fossil energy. We could trace its origin in the sun and its conversion by photosynthesis and biological decay to its extraction in the form of oil (hydrocarbons) from a well. Its path could be followed further as it is refined to gasoline or diesel fuel and then burned in the engine of a car, in part transformed into useful work and in part dissipated through road friction and aerodynamic resistance, and then returned to the environment in the form of heat and air pollution. (It is important to stress that the combustion of the hydrocarbons in the engine produces carbon dioxide and other by-products—as is the case with the burning of other natural materials such as wood or coal—that contribute in a major way to air pollution.) A similar example of an energy path is the transformation, utilization, and dissipation of energy contained in food.

The Concept of Information

The following topics could be included under the concept of information:

- The formal definition of information and its relation to probability (for example, the more surprising a message is, the more information it carries).

- The concepts and units by which we endeavor to quantify information and information flow (for example, words, bits, and bits per second).

- Errors; and redundancies and their use in reducing errors (for example, by repeating a message).

- The way in which information can be elaborated (for example, by computation or pattern recognition), carried (messages from transmitter to recipient), and stored (for example, in data banks).

- The physical means of conveying and storing information and the limits imposed by nature (how much can we convey? how fast?); and energy and materials requirements (for example, the electric energy needed to convey a telephone message).

- Examples of information processes in a social system (for example, learning), in a biological system (for example, in the genes, the nervous system, or the brain), and in a human-engineered system (for example, in computers, writing systems, and radar).

- Strategies for acquiring and using information (for example, getting the most information from a deep-space probe with a low-power transmitter—or even the very simple problem of weighing an unknown object using a minimum number of steps, given a set of known weights); and energy savings achieved through information (for example, avoiding wasted motion, be it in factory work, restaurant operations, or a variety of other activities that ultimately—through their efficiency—determine the economic competitiveness and wise utilization of resources, human and otherwise, of a society).

- Information paucity and information overload (an overload is a function of time—that is, of the speed with which information is processed).

The Concept of Systems

The following topics could be included under the concept of system:

- The definition of system (from the broadest definition as a group of entities working together or influencing each other to much more specific ones, such as those involving explicit and clearly characterized interactions or feedback loops).

- How to recognize and construe systems, both abstract and concrete, and natural and human-made (for example, a planetary system, an ecological system, a school, a television network, a factory that makes television sets, a pen, a car, a corporation, or a state); and system hierarchies and system components.

- Systems in static equilibrium versus systems in dynamic equilibrium (for example, a house versus a moving airplane or bicycle).

- The role of feedback and feedforward (for example, the thermostat in a room, or the eye/brain system for approximating the height of a stairway we are climbing); self-adaptive systems

(systems adapting their characteristics and performance to changes in the environment) and their possible degeneration to autonomous systems (systems not responding to the environment); and how a purposeful, self-adaptive system must possess a model of its environment (the importance of knowledge).

- Changes in system properties with size—a topic that can lead to a discussion of how individuality is born out of complexity (we are all made of the same basic atomic building blocks, yet we are all different).

- How to recognize system failures, component failures, component mismatches, and failures at the interfaces between systems; and the problem of complexity at interfaces (for example, how to match the high speed of airplanes with the relatively slow reactions of pilots).

OTHER UNIFYING CONCEPTS

A number of other general concepts are also important to an understanding of a broad range of phenomena and processes in the physical and information sciences and in engineering, and they often cut across the key unifying concepts we have just suggested. For example:

- *The concept of equilibrium* is involved in the movement of a seesaw, in the stability of a structure, and in the reaction rates of chemical processes, including the concept of buffer as a substance that maintains chemical equilibrium.

- *The concept of time rate* describes the flow of water, materials, energy, or information, such as the flow of a liquid in a pipe, the daily output of a factory, the cooling of a body, the progress of a chemical transformation, the transmission capacity of a telephone line, or the climbing performance of an airplane.

- *The concept of conservation* expresses fundamentally the idea that some things are always conserved, such as momentum, energy, and parity—and specifically that matter and energy are indestructible and can only be transformed (from one form to another and into each other), so that the energy and matter within a system (for example, a house furnace or a human digestive tract) can be tracked and budgeted.

- *The concept of efficiency* defines the ratio of useful energy obtained from a machine to the energy supplied to the machine. The term "efficiency" has come to be used by society at large to describe, in a generalized way, input/output relationships in all sorts of physical, biological, social, engineering, and information-processing contexts.

- *The concept of uncertainty* stems from our inability to measure perfectly or calculate completely all the elements in a system—and hence the need to resort to probabilities. The concept has a very precise formulation in the case of a microscopic physical system (Heisenberg uncertainty principle).

- *The concept of risk*, similarly, is of a probabilistic nature. It involves the probability of an unfavorable natural event, such as a flood or an earthquake, or the probability of failure of one

of our human-made devices or processes, such as a satellite, a nuclear reactor, or open-heart surgery.

- *The concept of cost-effectiveness*, although of an economic nature, is important to engineering. For example, consider the cost required to build an artifact, such as an airplane or a pollution-control device that will perform with a certain effectiveness (for instance, an airplane that will fly a given distance at a given speed or a device that will remove a certain type and amount of pollutant). It is important to keep in mind, however, that cost is not the primary or only measure of the value of an engineering project, since potential benefit must have other dimensions as well. How could one assess in dollars, for instance, the effectiveness of a pyramid or the pleasure derived from watching a concert on television? Beyond engineering, the concept of cost-effectiveness has come to be used in the sciences (for example, how much does it cost to launch a space probe, and how much information do we derive from it?) and in other human activities.

The concept of benefit analysis, which is related to that of cost-effectiveness, is another important general concept. It deals with the assessment of the benefits brought about by a given human action or artifact. For instance, in health care, how much benefit do we derive from screening a population for lung cancer once a year—and at what risk? Again, there are inherent problems in translating an intangible, such as the value of health or human life or ecological preservation, into a tangible, such as dollars. Potentially cost-effective airplanes, for example, may never be built owing to non-cost-related considerations, such as environmental damage; conversely, it may be beneficial to engage in engineering projects—such as providing facilities for people with disabilities—that may not be cost-effective in some sense.

To reiterate, general concepts such as those summarized above have acquired significance beyond the physical and information sciences and engineering, so that we talk of political or ecological equilibrium, of rate of progress or inflation, of oscillating or drastically unstable financial markets, or of conservation of natural resources. Thus, these concepts can help interconnect the physical and information sciences and engineering, other sciences, and (more generally) other aspects of society. For instance, one could discuss how the relative abundance or scarcity of mineral resources or the invention of increasingly effective ways of utilizing energy have influenced societies (for example, coal and the Industrial Revolution; oil and the automobile; and the OPEC countries). One could also discuss the historical trend in civilization from early societies dependent on materials and energy sources (primarily human and animal, plus the sun and wind) to the energy-rich societies of the Industrial Revolution, to today's societies in which information-related activities become the predominant occupation of the population (postindustrial service economies).

SECTION 6

KEY SPECIFIC CONCEPTS

The unifying concepts outlined above provide common threads that should serve as a useful guide to the spectrum of disciplines encompassed under the label of the physical and information sciences and engineering. High school graduates cannot be expected to be knowledgeable in all aspects of this spectrum. However, there are some key concepts specific to each discipline or group of disciplines—that is, to *physics and chemistry;* the *earth, planetary and astronomical sciences,* the *information sciences;* and *engineering*—that all high school students should have the opportunity to explore and understand, at least to some degree.

These key concepts are discussed in this section. For many of these concepts, the discussion includes a list of "relevant items." Such lists are not intended to be lists of topics that will necessarily be included in a curriculum; rather, they are presented simply as items that can be addressed to clarify or amplify a specific key concept. It is up to the teacher or student to decide how deeply to explore them. We stress that the key specific concepts provide a simple but solid disciplinary foundation that complements the unifying concepts, and they can be expanded as needed.

We leave open, furthermore, the question as to whether traditional disciplinary divisions—such as the one between physics and chemistry that we have eliminated here—should be preserved in school curricula in the future. Should the science disciplines be merged by focusing on unifying concepts (such as the ones identified in Section 5) and on the integrative approach to teaching (discussed in Section 7)? The answer will depend largely on each teacher's experience and success in the classroom. However, even if the disciplines are conceptually or pedagogically merged or integrated, there will continue to be a need for specific concepts and laboratories in physics, chemistry, computation, and so forth for specific sets of phenomena.

Given the central importance of mathematics for an understanding of the physical and information sciences and engineering, we strongly reiterate the need to teach it in an integrated fashion with these subjects. Most specific concepts in physics, the other physical sciences, and engineering can be approached in two mutually reinforcing ways—through experimentation and through mathematics. The integrative approach shows the clarifying and enhancing value of a mathematical description of a phenomenon.

To develop such a description, the student needs enough familiarity and experience with derivatives and integrals to be able to formulate laws of science more generally as differential equations. As an example, the normal distribution, or Maxwellian, can be understood simply through the shape of its curve. More precise understanding calls for knowledge of the exponential function, which is best defined as a solution of the differential

equation $y' = y$. Another example is Newton's second law of motion. This is most easily formulated in mathematical terms as the ordinary differential equation $m\,x'' = f$. Other fundamental conservation laws of physics and engineering have similar mathematical representations that are easier to learn than to circumvent.

Although these calculus concepts are not now within the realm of the typical high school graduate, we feel that they can be approached and understood, if only through difference equations or finite sums and averages. Teachers should not shy away from offering, albeit in simplified form, an understanding of some of the key equations used to describe physical reality. The sooner the student acquires an understanding of how the elements of physical reality can be powerfully described through the use of these equations, the sooner a great deal of science will become demythologized and the student will feel more comfortable with science.

PHYSICS AND CHEMISTRY

Physicists try to understand the world in terms of as few basic concepts as possible—concepts that not so much underlie as *lie within* all the other sciences. They focus on the nature and behavior of very simple systems such as atoms, and also on complex systems, insofar as the behavior of such systems is simple (in airless space, for instance, a mouse and a moon will fall at the same rate as a molecule).

Chemists endeavor to understand how the world works in terms of the behavior of the atoms and molecules of substances (reactants) that interact with each other to produce materials whose properties are different from those of the reactants.

We believe that experiments are essential to the development of an understanding of physics and chemistry concepts. School curricula should emphasize simple experiments that make the point but are not costly. Very simple "kitchen" experiments could even be started at the preschool level.

Key Concepts

- *All Physical and Chemical Phenomena Are Governed by a Few Basic Interactions*

Relevant Items[3]: The basic laws of gravity, electricity, and magnetism; the electromagnet; the gross characteristics of the strong and weak nuclear interactions; and the concept of a field to describe a force—for example, between two electrons—as the (electric) field of one or the other.

Comments: One central pursuit of modern physicists is to discover the unity of nature, as demonstrated in the identity of seemingly different fundamental interactions. In addition to being

[3] We emphasize the facultative nature of the relevant items as being guides for further expanding, when desired, some understanding of a key concept and its applications—but most emphatically not as obligatory topics to be taught or learned.

able to describe the main characteristics of these interactions as we know them today, students should be aware of the deep cultural and philosophical implications of this pursuit, as well as of its incomplete, ongoing nature.

- ***The Quantum Principle: On a Microscopic-Length Scale, Many Physical Quantities—Such as Electric Charge, Mass, and Energy—Are Found in Tiny Fixed Units Called Quanta; Atoms Gain and Lose Energy in Fixed Quantum Units***

Relevant Items: All matter is built up of particles. An atom consists of a tiny but relatively massive nucleus of protons and neutrons surrounded by a cloud of electrons equal in number to the protons. The stable existence of atoms (that is, chemical matter) requires quantized energy states of atoms, analogous to the separate resonant vibration frequencies of a violin string. Photons are quanta of electromagnetic energy.

Comments: Changes in the energy of a quantum system such as an atom or a nucleus are accompanied by absorption or emission of the precise energy difference in a quantum of radiation (photon) or as a change in kinetic energy—as occurs in nuclear fission or nuclear fusion. This concept, we believe, is easier for today's children to grasp than it was for adults when it first emerged in the 1920s. The quantum concepts apply to all materials, including biological materials. For instance, the eye detects photons; photons are also absorbed by plants in photosynthesis.

- ***The Behavior of Simple Static and Moving Systems Can Be Explained Using the Laws First Laid Out by Isaac Newton***

Relevant Items: Velocity; acceleration; rotation; force, work, power; friction; vector addition of forces; impulse, momentum, and angular momentum; and inertia.

Comments: Static and moving systems are a ubiquitous part of our everyday reality. Such a system may consist of a pulley, a house, a bridge, a car going around a corner, a bullet shot from a rifle, a boat, or an airplane. Students derive immediate practical benefits from learning to understand what happens—in terms of motion or internal forces—in a variety of such systems.

- ***Intuitive Ideas of Space, Time, Energy, and Mass Fail at Great Distances and When Speeds Approach the Speed of Light***

Relevant Items: Light from the sun takes 8.3 minutes to reach the earth. If a person in a spaceship could leave the Big Ben tower clock at 12 noon at the speed of light, he would never see its hands move, since the light from 12:01 would never reach him. Albert Einstein first postulated that moving clocks in general appear to run more slowly than clocks located with the observer (still a puzzle to the lay person). The speed of light, 186,000 miles per second, cannot be exceeded, and it has the same value when measured by any moving observer. The energy needed to accelerate objects to almost this speed vastly exceeds that calculated conventionally. Space travel at close to this speed, therefore, is not possible because of the energy cost.

Comments: Careful reasoning about space, time, and the fixed speed of light led Einstein to conclude that energy and mass are

equivalent, according to the rule $E = mc^2$, where E is the energy, m is the mass, and c is the speed of light. This is a working equation in nuclear reactions and nuclear power, where the kinetic and radiation energy released is calculated by taking m as the change in the rest mass of the nuclear fuel after reactions have occurred. The same rule can even be applied to chemical reactions (for example, in an explosion of TNT), but the change in mass is much smaller. An example of a process of direct and complete conversion of rest mass to energy occurs when an electron and a positron (positive electron) annihilate.

- ***Electromagnetic Radiation, of Which Light Is an Example, Occurs in a Very Large Range of Wavelengths; Such Radiation Is Emitted and Absorbed as Particles or Bundles of Energy***

Relevant Items: Lenses and mirrors; reflection and refraction; interference; diffraction; polarization; characteristics of the emission, absorption, and propagation of electromagnetic radiation from radio and television signals to x rays; color and the human visual system; photoelectric effect; and photons and the idea of the quantum.

Comments: Many of these phenomena can be demonstrated by means of relatively simple examples. Since humans assimilate a considerable amount of information visually, the explanation of human vision and its limits provides a particularly immediate link between physical ideas and the world around the student, helping to bring science closer to home. Students should be able to explain a good sampling of common optical phenomena, such as reflections in a shiny spoon, infrared photographs, and rainbows. Understanding the relationship between the dormant color of a glowing body and its temperature leads to the idea of the quantum.

- ***Electrical Phenomena Can Be Understood in Terms of the Behavior of Electric Charge***

Relevant Items: Electrons flowing and carrying information and energy; static electricity; lightning; current, voltage, and resistance; capacitance; batteries; electrons flowing from a hot filament to a target; cathode-ray tubes; and overview of solid-state electronics—for example, the transistor.

Comments: The ability to understand these concepts—developed through demonstration (often relying on very simple circuits)—is of great practical value for citizens confronted with all sorts of electrical and electronic devices. Also of value to them are knowledge of basic computer architecture (including the typical components and how they are connected) and an understanding of the hazards of electric currents and how to avoid such hazards.

- ***For Many Purposes, Matter Can Be Viewed as Being Composed of Atoms and Molecules That Have Well-Defined Sizes, Shapes, Structures, Compositions, and Energy Contents***

Relevant Items: The historical development of chemistry and of the atomic theory, what causes the atoms of the various elements to be different (subatomic structure), the electronic nature of chemical bonding (why some atoms stick together

readily and others do not), valence, types of chemical bonding (covalent, ionic), why bonds have spatial direction, molecular isomerism (for example, how many molecules have the empirical formula C_6H_{14} and what are their structures?), atomic and molecular dimensions (compared to dimensions with which students are familiar), and how molecular compositions and structures are determined (use of modern analytical instrumentation, such as infrared and ultraviolet spectrometers).

Comments: If students think in atomic and molecular terms, they will be able to gain the insight that chemistry provides into the behavior of physical systems. Systems of actual or potential interest to the average citizen can range in size and complexity from the subatomic to the universe as a whole.

- *Atomic Nuclei Undergo Changes*

Relevant Items: Radioactivity (types, sources, methods of detection, isotopes, half-lives, and biological impacts), nuclear energy (fission and fusion, methods of control, and conservation of energy and matter), the transmutation of elements, and the synthesis of new elements.

Comments: These changes are related to the basic structure of matter. It is essential that citizens be familiar with some manifestations and effects of these changes, such as x rays, luminous watches, nuclear magnetic resonance, nuclear power, and solar radiation.

- *Energy and Matter Manifest Themselves in Many Ways, Are Transported and Transformed, and Are Conserved*

Relevant Items: Forms of energy—mechanical, sensible and latent heat, electromagnetic, chemical, electrical, nuclear; the conservation of matter and energy; the first and second laws of thermodynamics; energy efficiency; the generation, conversion, storage, and transport of energy, especially heat flow.

Comments: The pendulum provides a very simple demonstration of energy conversion (from kinetic to potential and vice versa). Much of the sound reasoning in the domain of the physical sciences that will be helpful in everyday life comes from a clear understanding of the budgeting and conversion of matter and energy. Questions such as "Tell what is happening with matter and energy when you carry a pail of water upstairs and throw it out the window" can guide a student to this type of thinking. The topic is particularly important as a basis not only for physics and chemistry but also for other sciences such as biology, and for engineering.

- *The Behavior of Matter Under Various Common Circumstances Is Dependent On Its Physical State (Solid, Liquid, or Gaseous)*

Relevant Items: Brownian motion (for example, how do molecules move around in air and in water?); the molecular basis of temperature and pressure (for example, when a rubber band is stretched, why does its temperature change?); phase transformation; simple hydrostatics; fluid pressure laws; steady flow versus turbulence; oscillations, water waves, and sound waves; earthquakes; and resonance.

Comments: Examples of how the behavior of matter is dependent on its physical state abound in everyday life. The ability to explain that behavior in broad terms helps us, for instance, to better understand ourselves as fluid organisms (blood, circulation, respiration, cell fluidity, synaptic transmission of information, hormones, etc.) and our environment (air, water, and solids). Very simple experiments involving fluid pressure can be performed using a bicycle pump or using a liquid-filled plastic tube; phase-change experiments can be done using dry ice or a kitchen stove; and turbulence experiments can be done using a smoke source. Students' mathematical understanding should advance to the point where parallels can be drawn among some of these phenomena, as well as with phenomena in systems outside physics (for example, oscillations in liquids and solids, and liquid analogies to traffic flow).

- *Matter Undergoes Chemical Transformations (Reactions) Whose Nature and Occurrence Are Dependent Upon the Intrinsic Features of Atoms and Molecules and Upon the Surrounding Environment*

Relevant Items: The difference between physical and chemical changes, strengths of chemical bonds, attractive and repulsive chemical forces, periodicity of the elements (with respect to both structure and properties), elementary thermodynamics (concepts of entropy and free energy), conservation of mass in chemical and physical changes, and why chemical phenomena are reproducible.

Comments: The conversion of matter into other forms is observed daily by all people, but the difference between physical and chemical changes is not commonly perceived. To comprehend how the world works, citizens should understand that phase changes (physical changes, such as steam to liquid, and water to ice) are reversible and do not bring about fundamental alterations in the properties of matter; on the other hand, chemical transformations (for example, combustion) frequently are irreversible and lead to changes in matter at an extremely basic level.

- *Chemical Transformations of Atoms and Molecules Produce Materials Whose Properties Differ From Those of the Reactants*

Relevant Items: Acid/base reactions, oxidation and reduction (combustion, rusting, electrochemistry, and batteries), polymerization, stoichiometry (the laws of chemical combination), the synthesis of celluloid and new materials (drugs; plastics such as polyethylene and polyvinyl chloride; fibers such as rayon and nylon; electronic materials; etc.), the effects of chemical change on local and global environments (the greenhouse effect, acid rain, and depletion of the ozone layer), chemical changes in living organisms, biopolymers (polypeptides and polysaccharides), chemical raw materials (aluminum, sulfur, and petrochemicals—their uses and their extraction from natural sources), how macroscopic properties depend on atomic and molecular properties (why are metals shiny and why do organic dyestuffs have various colors?), and energy storage by molecular systems (chemical techniques for storing solar energy).

Comments: Chemical changes brought about by humans have produced an enormous number of new and useful synthetic materials. Yet, the industrial production of these materials has led to environmental problems. Any unknown chemical (and most chemicals are unknown to the public) should be approached with caution. Students could learn to perform their own risk/benefit assessment of these matters in an enlightened fashion. Like synthetic chemical changes, natural chemical transformations (defined as those not involving human intervention) may be either beneficial (for example, life processes) or deleterious (for example, the rusting of iron).

- *The Rates of Chemical Reactions Are Determined by the Atomic and Molecular Properties of the Reactants and by the Reaction Environment*

Relevant Items: How rates are affected by bond strengths and molecular geometry (simple examples from organic chemistry), how bonds cleave, reactive intermediates (ions, free radicals, and other metastable species), catalysis (catalytic cracking in the petroleum industry), chain reactions (for example, hydrocarbon autoxidation), the effects of reaction variables (media, temperature, and pressure) on the reaction rates, the concepts of activation energy and the activated complex, photochemistry, the nature of chemical equilibrium behavior, and a reiteration of the general relevance of the equilibrium concept to various types of systems (for example, a buffered solution, a seesaw, a lever, a biological ecosystem, or a city).

Comments on the Teaching of Chemistry

As stressed above in Section 1, the context in which science is taught is as crucial to learning as the curriculum itself. This is particularly important in the case of chemistry. In the past, science teaching in the schools has tended to focus on chemistry per se, rather than on its pervasive influence upon many types of phenomena that can be observed by the physical senses. As a result, students have usually been unable to think about such phenomena in molecular terms; that is, how the properties of individual molecules contribute to the behavior of large and small systems. More specifically, most students have not been guided to appreciate the real-world relevance of the concepts of molecular size, shape, structure, and reactivity (for example: How big is an atom? How many atoms and molecules are contained in macroscopic objects? How do the size and geometry of molecules influence their efficacy as drugs? Why is rubber an elastic material? Why do perfumes have pleasant odors? How do molecular composition and reactivity lead to the problem of acid rain?).

The general public usually thinks of chemicals as being artificial substances that have societal benefits in some cases but are responsible for unpleasant smells, major health problems such as cancer and chronic respiratory diseases, and the destruction of the environment. This stereotyped image of chemistry and chemicals needs to be corrected by teaching (1) the pervasiveness of chemicals (all matter above the subatomic level is composed of chemicals), (2) the need for caution in producing and using

chemical materials, (3) the actual and potential contributions of chemistry to the solution of existing social and environmental problems (for example, chemical contraceptives, atmospheric chemical analysis, and laboratory reactivity studies pertaining to the ozone-layer problem), and (4) the other societal benefits of chemistry.

EARTH, PLANETARY, AND ASTRONOMICAL SCIENCES

The earth, planetary, and astronomical sciences differ substantially from such sciences as physics, chemistry, and biology in that experimentation is not always possible. Continents, and the forces that drive them to collide, can hardly be created in the laboratory. Nor can the evolution of a star be duplicated on earth. Instead, many earth and planetary scientists and astronomers must make use of only what they can see and record, and must resort to generalizations, models, and analogies. Nature itself becomes the laboratory, and we must seek out the experiments nature is running at present, observe them and generalize from them, and then go to new places to observe nature's new experiments.

The earth and related sciences often rely on the concept of *process*, by which large-scale objects interact in predictable ways. Thus, we speak of the process of glaciation, in which ice moves from mountain peaks and landscapes are carved. Although we could try to reduce this process to the physics of atoms of solid water moving under the influence of gravity, it is often more useful to consider the glacier itself as an agent of erosion that produces distinctive landforms. Understanding the process, therefore, requires a different level of abstraction than does the mastering a law of physics or chemistry. But a sound knowledge of the underlying physics and chemistry is usually essential for a thorough knowledge of the process. In fact, many basic concepts in physics, chemistry, biology, and even mathematics can be taught within the context of the processes studied in the earth, planetary, and astronomical sciences.

Study of the atmosphere and oceans is essential to an understanding the earth's surface. These fluid layers are the global transportation networks of heat, and they create climate and weather and serve as buffers to maintain environmental equilibrium (homeostasis). They are responsible for the origin and ultimate preservation of life on our planet. Thus, oceanography and meteorology, the sciences that study these layers, although relatively new, are of great importance in secondary and elementary school curricula. Therefore, we have included several key concepts from these fields to help teachers and students. We have chosen to arrange these concepts to proceed from the universe to our galaxy to the solar system to the earth. Obviously, other sequences may be preferred (for example, starting from the earth).

Key Concepts

- *Our Universe Has an Enormous Number of Galaxies*

Until modern times, humankind had little but myth and speculation in the way of information about things beyond the earth.

However, we now realize that our universe has an enormous number of galaxies, each with an enormous number of stars of various kinds, many of them similar to our sun. Currently, we believe that this universe originated 15 or so billion years ago as an extraordinarily hot, dense mass of elementary particles—a mass that is still expanding and cooling. From the gases, stars coalesce, and within their furnaces the chemical elements are built up. Some stars explode, and from the resulting clouds new stars and also planets coalesce.

Relevant Items: The history of astronomy; instrumentation to study things beyond reach; energy and mass in the universe; hints about cosmology and its relation to particle physics; galaxies; the varieties of stars and a glimpse of their evolution; the "ecology" of galaxies; nuclear reactions; the origin and relative abundance of the elements; and speculations about the formation of planetary systems.

Comments: This topic is worth studying not only for its direct practical value but also because it answers deeper needs, such as to know what can be known about ultimate origins and destinations and about the place of humanity in the cosmos. The topic therefore calls for particular efforts to relate scientific ideas to our highest ideals, as expressed in religion, literature, and the arts. Along the way, space science serves as a useful way to introduce or review some features of physics. It is also a rich source of understanding for the history of the scientific method, and especially for how we study things far beyond our immediate grasp.

- ***The Sun Is One of the Many Stars Within the Milky Way Galaxy; the Earth Is One of the Planets of the Sun***

Our sun is one of many stars within the Milky Way galaxy, but to reach any other star—even the one closest to the sun—at current rocket speeds would take tens of thousands of years. The sun's energy comes from nuclear reactions deep within it; this has been going on for several billion years and will go on for several billion more. Most of the sun's energy flows out as light, but great surface explosions also affect the space around the sun. A number of planets and moons (and rocks, dust, and ice) orbit within this space. They have strikingly diverse characteristics. Only one of these bodies can readily support human life, and it does; that is the earth.

Relevant Items: The nuclear source of solar energy and its regulation; comparison with controlled thermonuclear fusion in the laboratory; the lifetime of the sun; solar weather and the space environment; meteorites and comets; other planets, especially in comparison with the chemical composition, geology, climate, etc. of the earth.

Comments: Some of the subjects involved also have very important if indirect practical value—for example, the calendar and its impact on agriculture, navigation (and at times its impact on mathematics, chronometry, and instrumentation), navigation satellites, space probes (and their impact on miniaturization), and the understanding that life on the earth depends on a delicate balance between enormous forces.

• *The Earth Is a Nearly Spherical Rotating Body; Its Dimensions, Motion, and Position Relative to the Sun Govern Our Lives*

The earth rotates once in 24 hours, producing the apparent motions of the sun and the moon. The rotating earth revolves around the sun, and the tilt of the earth's axis produces the seasonal variation in climate that most of the earth's surface observes. Features on the spherical—or nearly spherical—surface of the earth can be projected onto a flat plane to yield a map of their locations.

Relevant Items: Direction; time; seasons and the calendar; the path of the sun in the sky; the motion of moon and eclipses; latitude and longitude; the continents, oceans, and other major physical features; basic political geography; and maps and map projections.

Comments: Time, seasons, the motions of the sun and moon, the calendar—these are associated with many aspects of everyday life, from laying out a garden plot to making a transoceanic phone call to tying a boat up at a dock. Further, many surveys have shown how ignorant young Americans are of the places and features on the earth's surface.

• *Forces Deep Within the Earth, Acting Over Geologic Time, Have Caused Continents to Move, Rupture, and Collide*

Ocean basins have opened and closed as well. These forces have also caused earthquakes to shake and break the earth's surface, and have produced volcanic eruptions of molten rock released at the surface or within the solid rock layers of the crust.

Relevant Items: The interior structure of planets; earth materials such as rocks and minerals; volcanism; earthquakes; the interior structure of the earth; heat flow and convection in the earth's mantle; the continental and oceanic lithosphere; plate tectonics (theory and evidence); the breakup and movement of lithospheric plates; seafloor spreading; mountain building; shearing; the evolution of the earth; historical aspects; and comparison with the tectonics of Mars and Venus.

Comments: As a grand unifying theory, plate tectonics is as important to geology as evolution is to biology. Even a simple understanding of this theory helps to explain the shapes and positions of the continents on a global scale; at a more detailed level, it explained the patterns of ranges and rifts, plateaus and piedmonts on the continents. Even the distribution of mineral deposits, especially metallic ores, can be fitted to the pattern of plate movements and history. Alfred Wegener's theory of continental drift, now universally accepted on the basis of plate tectonics, can provide students with a good example of the difficulties with which a good idea must often contend in order to be accepted. The theory was first rejected on the basis of energy considerations, and Wegener died before his theory was vindicated.

• *Life on the Earth Arose Through Natural Processes Several Billion Years Ago*

Life-forms have continually changed since their first appearance through the process of evolution, mutating and adapting

through selection until there is virtually no place on the surface of the earth without some form of life present. The presence of life has greatly altered the earth's surface environment—producing, for example, an atmosphere containing an abundance of oxygen and a reduced amount of carbon dioxide.

Relevant Items: The origins of life—primordial soup; primitive life-forms; the fossil record; evolution; continuity and jumps; cataclysmic events; the influence of life on the earth's surface, oceans, and atmosphere through geologic time; plant and animal taxonomies; the true nature of species, genera, families, and higher classification units; ecology; niches; the threat to human life of harmful viruses and bacteria; and the question of extraterrestrial life (in the solar system, an average kind of system, and therefore the possibility of life in this galaxy or other galaxies).

Comments: Appreciation of such important ecological topics as tropical deforestation and its biological implications requires a comprehension of the vastness of geologic time and the continuity of the evolutionary process. Further understanding of how life has modified the planet over millions of years (for example, by raising oxygen levels and reducing carbon dioxide levels, thus paving the way for photosynthesis in terrestrial autotrophs) can help convey the seriousness of the possible implications of human activity on the habitability of the earth.

- ***The Oceans and Atmosphere Are Very Large, Buffered Chemical, Biological, and Geological Systems***

Although the earth's oceans and atmosphere are very large, they have only a finite capacity to withstand change without generating tremendous climatic alteration. The ocean/atmosphere interaction represents a huge interwoven system that is driven by solar heating combined with the rotation of the earth and the orbit of the moon. The hydrosphere is the site of most of the life on our planet, generating an immense system of gaseous interchange with the atmosphere above it.

Relevant Items: The origin of fluid envelopes; the composition and temperature of ocean water and the atmosphere, including changes associated with depth and altitude; the ice caps; the ocean basins and the topographic features of the ocean floor; the vertical structure of the oceans and atmosphere; upwelling and nutrients; chemical cycling through heating from mid-ocean ridges; air/ocean interactions: wind-driven circulation and density-driven currents; the stratification of life in the oceans; and the human use of the oceans for transportation, warfare, minerals, and resources (fish, fuel, gases, and building materials).

Comments: Heat flow at the air/sea/land interfaces and fluid circulation in the atmosphere and hydrosphere are the primary determinants of climate. Disturbances in the ocean/atmosphere system, such as El Niño, can wipe out a year's crop yield and throw the world's economic and agricultural systems out of balance. A well-informed citizenry should be aware of these global effects and the interrelationship among the supply of nutrients in the oceans, the balance of carbon dioxide in the atmosphere, and widespread climate change.

• *Climate Is the Long-Term Expression of the Movements of Masses of Fluids in the Oceans and the Atmosphere*

Water absorbs surface heat when it evaporates from the ocean or from a moist land surface; when the water vapor condenses, it releases this heat to yield precipitation. Fluid motions in the oceans and atmosphere serve to transfer heat from areas of surplus to areas of deficit. When one air mass invades another, and also interacts with topographic features, the weather changes. Climate is the long-term expression of these mass movements, including the interaction of these movements with topographic features. The earth's climates have changed radically in the past and may well change in the future, naturally, as a result of actions of the human species, of the impact of meteorites, or of the effects of other agents.

Relevant Items: Energy flow and transformation in the atmosphere and at the air/sea/land interface; weather (storms, fronts, precipitation, and air masses); microclimates on the human scale (for example, the siting of houses); climates and their geographical classification; climatic change and past climates, including changes in sea level; and the atmosphere and climate on other planets (Mars and Venus).

Comments: This topic offers a good chance to show how highly complex phenomena of immediate practical concern can be explained, if not always predicted. Weather affects our everyday activities and is discussed daily on radio and television. Severe weather can be a major natural catastrophe. A focus on climate also offers a chance to study folklore ("red sky at morning," etc.) for its truth content or lack thereof. Descriptions of clouds and storms in art and literature, as well as in science, point up the different ways of perceiving things, while showing that the human eye sees both more and less than a formal description contains. The availability of water, sunlight, and moderate temperatures controls the pattern of human settlement and agricultural development on the earth's land surface. Climate and its changes will be of great immediate concern as concentrations of carbon dioxide and other climate-influencing atmospheric gases increase and the earth's climates undergo major geographic shifts.

• *Waves, Wind, Water, and Ice Are Agents of Erosion and Deposition That Sculpt the Earth's Surface to Produce Distinctive Landforms*

Because the mineral surfaces of landforms are exposed to air, plants, and animals, chemical and biological reactions differentiate these surfaces to form soils reflecting both present and past reactions. Since the amount of the various elements at the earth's surface remains relatively fixed, certain elements—such as carbon, oxygen, nitrogen, and sulfur—can be thought of as going through a cycle in which they move from one form and location to another under the influence of surface processes. In another cycle, rock is weathered to mineral particles; moved to regions of accumulation; buried and subjected to heat, pressure, and mineral solutions; and eventually turned to rock again.

Relevant Items: Mountain- and basin-making processes; erosion and deposition; landforms and landscapes; rivers, wind, waves, glaciers, and tides; soils (nature, distribution, creation,

and destruction); the rock cycle; material cycles (carbon, oxygen, nitrogen, sulfur, etc.); and human influences on surface processes.

Comments: This topic is obviously of great importance in understanding how the earth's surface has obtained, and is obtaining, its present form. This knowledge is useful for buying a house, planting a garden, or even looking out of the window of an airplane. Further, it opens the eyes of students to the world around them—a world of landforms and landscapes created by ongoing geologic and geomorphic processes. Material cycles, though less visible, are important; the problems of atmospheric carbon dioxide and acid rain, for example, are but parts of the carbon and nitrogen cycles.

- ***Humans Need and Use Many Substances Found Naturally on the Earth's Surface and in Its Interior***

Some of the earth's resources are nonrenewable, including minerals (pure crystalline compounds) and also rocks, which consist of assemblages of minerals. A knowledge of the processes that act both within the earth and at its surface can help students to understand the location of the earth's resources. The nonrenewable resources of the earth are finite, of course, although the substitution of one substance for another can sometimes prolong the availability of a particular resource. Renewable resources include water, wood, and solar energy. As water moves from ocean to land and back again, it is channeled, diverted, and processed to supply human needs. Plants live largely on the constant energy of the sun, producing wood that humans can use for construction and burning, food crops for consumption, and many other useful substances. Through modern technology, energy from renewable sources such as the sun, wind, or tides can be harnessed to provide electricity, or can be stored in chemical forms for later use.

Relevant Items: Minerals—their nature and properties vis-à-vis chemical composition; rocks and rock-forming processes; ores and mines; the location and availability of mineral deposits; links with plate tectonics; fossil fuels; solar energy; alternative energy sources; nuclear energy; renewable resources (their nature and distribution—for example, of forests); economic biology (organisms as sources of useful materials); and agriculture.

Comments: An understanding of the uses, availability, and dependence of society upon natural resources is crucial for present and future political and economic awareness. A key example is our growing dependence upon Third World oil reserves, which in itself has been a cause of much of the international tension associated with the Middle East. In a world of declining resources, it will be increasingly important to deal with supply and demand and to protect the valuable resources that help to define our present-day standard of living. Future generations will have to be aware of the distribution of resources to provide input in governmental affairs.

- ***All Places on Earth Have Characteristics That Give Them Meaning and Character and That Distinguish Them From Each Other***

These characteristics include the physical setting and the characteristics of the human social environment, such as settle-

ment patterns, architecture, economic activities, and transportation networks. People perceive characteristics of places according to their own experience or points of view. They modify or adapt to natural settings in ways that reveal their cultural values, economic and political circumstances, and technological capabilities. Goods, people, ideas, and technology move from place to place in patterns that geographers study. Through their activities, humans constantly change the earth's surface, oceans, and atmosphere. Mostly, the changes are helpful, from a human viewpoint, but sometimes the changes are harmful—as in instances of pollution, coastal erosion, and war.

Relevant Items: The physical environment; natural disasters; earthquake, flood, and storm prediction; economic geography; diffusion and gravity models; environmental perception and mental mapping; transportation and interregional flows; regions and cultures; pollution; sewage and industrial wastes; the effects of modern wars; the global impact of carbon dioxide, ozone, methane, and fluorocarbons; nuclear winter; acid rain; etc.

Comments: Managing the earth is a complicated job that requires careful planning, knowledge, and understanding. Directly or indirectly, all of the earth's inhabitants are involved in this management. A firm knowledge of the earth's geography—including the human, cultural, economic, and physical processes that occur on the planet's surface—is essential for the citizens of the twenty-first century.

INFORMATION SCIENCE AND COMPUTER SCIENCE

Key Concepts

The first five concepts discussed below are strongly related to information science. The next three concepts are usually identified with computer science. The remaining five pertain to both information science and computer science.

- *Information Is the Meaning Attributed to Data*

Information can be conveyed by natural phenomena such as tree rings, layers in rocks, radiation from deep space, and DNA molecules. Humans, too, convey information in many ways—for example, through the use of language, music, or gestures.

Information can be formalized as the reduction of uncertainty. When one finds out which way a coin landed, for example, one acquires one bit of information (see discussion below about forms of information). Information theory (applied probability) has extended this idea to determine the information content of a message or the capacity of a system.

Comments: Information is a real entity (albeit an abstract one) of practical and commercial value, and it is a useful concept for understanding physical, biological, and social systems and phenomena. It is always instructive, for instance, to look for the information flow within a system. Knowledge expresses validated generalizations about a given domain (for example, "penguins do not fly") and the rules for applying these facts to accomplish a task (for example, how to take care of penguins). Thus, knowledge is an important activity in building information systems

known as knowledge-based systems. It is important to understand how knowledge is acquired for these systems, and how descriptions may interact with existing knowledge (for example, "birds fly") to either substantiate or modify this knowledge (for example, "but penguins do not fly"). It is also important to understand how knowledge is used, to build models that explain events and situations, to find solutions to problems, and to categorize information for subsequent retrieval.

- ***Different Kinds of Information Can Be Derived From the Same Data***

The information that humans obtain by perceiving patterns in data is defined by the purpose for which it is gathered. Thus, the kinds of information obtained from the rings of a redwood tree depend on whether we want to know the age of the tree, the health of the tree, or the climate during the years when the tree was growing. Similarly, the information derived from a passage in a science textbook may be used for learning a new discipline, updating one's knowledge about a discipline, writing a review of a discipline, answering questions in an exam, critiquing the textbook, or studying technical writing. Generalized factual information (knowledge) may be used for solving a problem, explaining an event or situation, or categorizing the descriptions of events and situations.

- ***Information Can Be Expressed in Many Forms and Can Be Represented in Analog (Continuous) or Digital (Discrete) Formats***

Comments: A major discovery by Claude Shannon (and others) is that these forms are equivalent and interchangeable. Analog and digital clocks convey the same information. Collections of Boolean (two-valued) variables called bits can be used to represent digitally *all* forms of information (numbers, words, pictures, graphs, sounds, etc.) to any desired degree of accuracy. Most human-made information-processing systems use the digital form of representation. The representation of knowledge (information) in all of its various forms is a major theme in information science.

- ***Information Generally Degrades During Transmission or Storage***

Spoken messages are misunderstood, photographs fade, and computer memory cells are disturbed by cosmic rays. There is no law of conservation of information.

Comments: It is easy to demonstrate that information degrades, and how redundancies can remedy the loss. Mathematical techniques have been devised to detect and correct errors.

- ***All Systems, Both Natural and Human-Made, Are Internally Coordinated by Processes That Convey Information***

A system is a group of components working together or influencing each other—that is, communicating with each other in some way.

The components of a piano communicate by means of mechanical linkages. The components of a computer system communicate by means of electrical currents in copper wires or

optical pulses in fibers. The components (in this case, successive generations) of a biosystem communicate by means of DNA molecules within seed cells. A black hole can be said to communicate with nearby stars—that is, send "I am here" messages—by means of gravitational attraction.

Comments: Some people prefer to exclude the mechanisms that link the components of nonliving natural systems from the definition of information. Whatever they are called, however, these mechanisms can be analyzed as if they were information mechanisms.

- ***Information Is More Useful When It Is Represented by Orderly Collections of Symbols Called Data Structures***

Humans use tables, indices, alphabetical lists, file cabinets, and the Dewey decimal classification system to organize large amounts of data. Information-processing machines also benefit from the use of the above data structures, as well as arrays, linked lists, files, and knowledge bases (lists of facts or rules used by artificial intelligence programs).

In computerized information-retrieval systems, data structures that capture the terms in a searcher's input are matched against data structures that index (that is, point to the location of) the information in the data base.

Comments: The point is that "getting organized" is more than just being neat; it is an essential part of manipulating information. Knowledge is virtually useless unless it is organized. Thus, a well-written science textbook presents knowledge organized in a way that is meaningful to the readers.

- ***Procedures Can Be Formalized as Algorithms***

An algorithm is an explicit procedure for computing a result. We are following algorithms when we perform long division, sort a list of names, or find the phone number of the police department in a distant city. Physicians are using algorithms when they interpret symptoms and tests.

A computer program is an algorithm, written in a language that a computer can interpret. A computer program that solves a problem that is normally thought to require human intelligence—for example, medical diagnosis—is called an artificial intelligence program. A key characteristic of such a program is its ability to make inferences from a set of premises.

Students can gain an understanding of these concepts by being exposed, for instance, to Euclid's algorithm for the greatest common divisor, selected numerical methods, algorithms for sorting, or heuristics (algorithms for intelligent guessing). They can benefit from examples that illustrate how to formalize seemingly informal and intuitive processes.

Comments: The great mathematicians were experimenters, devising algorithms to test their theories—that is why we have algorithms named after Isaac Newton, Leonhard Euler, Carl Friedrich Gauss, etc. All students should endeavor to have a direct experience with formalized procedures by writing at least one meaningful program before they attain voting age. They

should also learn to handle electronic mail, a word processor, a data analysis program (including a spreadsheet), a simulation of some kind, and a remote, large-scale data base.

- ***Computing Machines Are Constructed From Simple Components***

Computing machines are not magic boxes; they are ordinary machines that can be understood by any educated citizen.

The main subsystems of a computing machine are the processor, fast memory, file memory, and devices for communicating with the outside world. Each of these subsystems is constructed from simple, cell-like components called gates, which perform elementary Boolean logical operations such as "and," "or," and "not."

Charles Babbage conceived the general-purpose computer in the mid-nineteenth century; John von Neumann is responsible for the first modern design.

Comments: Just as every driver needs to know the rudiments of how automobiles work, every information-system user needs to know the rudiments of how information machines are constructed and operated. Every student should have the experience of plugging in a few cables and cards to prove that a lightning bolt will not strike him or her dead.

- ***All General-Purpose Computing Machines Are Fundamentally Equivalent***

In 1936, Alan Turing defined a primitive computer for use in the theoretical analysis of computation. He proved that any algorithm that could be programmed for a general-purpose computer could be programmed for this so-called Turing machine, and vice versa. This proof implies that all general-purpose computers are "Turing-equivalent," in the sense that any problem that can be solved by one can be solved by all. Turing also proved that there are problems that cannot be solved by *any* computing machine, either in the present or in the future.

There are many practical differences between computing machines. Different machines are tailored for different jobs, and they can differ enormously in speed of operation. Programs usually have to be recoded when they are moved from one machine to another. But the message of Turing equivalence is that fundamentally it is always possible to recode for another machine.

Turing's work, and the related work of others, begins to define what can ultimately be known by rational methods. These findings should be described, even if not fully understood, for they rank with the most significant scientific achievements and have deep implications for mathematics, computing, and philosophy.

- ***To Ensure That an Information System Will Be Successful in the Real World, the Design Must Include Both Logical Rigor and an Understanding of Social Forces, Cultural Beliefs, and Economic Realities***

Comments: Given this rich interdisciplinary blend, we must not equate information science with computer science. We do

not need a machine to make an information system. An information system is far more than mathematics, logic, and computer hardware. Philosophical and ethical considerations (human needs served by the system, privacy, acceptable risks, etc.) are often the most important design parameters.

ENGINEERING

Engineering is the practice of modifying nature to create systems (human-made artifacts such as instruments, bridges, airplanes, chemical plants, and computers and computer programs) that perform useful functions. Engineering thereby extends the reach of people's biological faculties—human muscles (extended, for example, by engines and explosives), human senses (extended by the telephone and television), human brains (extended by books and computers), and it is also beginning to modify our biological faculties themselves (as in the use of implants, prostheses, and biotechnology). The result is that humans have a growing ability to increase their control and utilization of the environment—not only on land but also on water, in the air, and (increasingly) in space. In creating human-made systems, engineering deals with the same main themes or unifying concepts as the physical and biological sciences, and is equally dependent on mathematics. Thus, engineering deals with materials, energy, information, and systems, as well as with the concepts of equilibrium, time rate, conservation, risk, uncertainty, and so on. The fundamental difference between engineering and the sciences is one of intent and of the method used to pursue that intent—that is, how the engineer goes about modifying nature.

Humankind's use of the most rudimentary tools to simplify physical efforts dates back to the earliest times of human development and is a key factor in differentiating humans from other species. Some of humankind's designs were remarkably effective and ambitious already in the ancient world (for example, sailing ships, temples, pyramids, bridges, irrigation works, and metal works). However, it was not until much later that design took a dramatic step forward in sophistication, when it could take advantage of the progress in the sciences ushered in by the Renaissance, and when it became imbued with considerations of cost, safety, and reliability. At this point, humans started to practice engineering (in the modern sense of the word) as the systematic, science-based design of the artifacts.

The engineer is basically a problem solver. Any problem—such as how to cross a body of water, fly, transmit information, build an artificial kidney, or maintain a fleet of airplanes—is typically approached by the engineer on the basis of analyzing the situation; developing a model of the problem; determining the constraints that apply to the solution (for example, those that involve size, materials, tools, instruments, labor force skills, and social and environmental impacts); developing a strategy or plan, and, if necessary, a model and a prototype for the solution; and, finally, designing and constructing the actual artifact (for example, a bridge, an airplane, a computer program, or a dialyzer) to achieve the goal.

The task of the engineer is not simply to design an artifact that works. The least costly artifact may not be the safest approach available; for example, leaded gasoline (in which tetraethyl lead is used to enhance the octane number of the gasoline) is less costly to produce and use than unleaded gasoline, but it results in the presence of potential hazardous amounts of lead in the atmosphere. On the other hand, the most expensive design is not necessarily the safest; for example, a luxury automobile may have fewer safety features than an economy car. Ethical considerations may be all-important, particularly when safety is a factor.

The concept of safety versus risk in engineering is more important today than ever before, and it will become even more so in the future. The challenge is to define "safe" and to apply a definition of it that is acceptable to society. Nothing is completely safe. Aside from the inevitable trade-offs between cost and safety, some engineering artifacts are exposed to natural hazards that are hard to predict with accuracy because of the randomness of certain natural phenomena, such as changes in global climatic patterns and severe floods or droughts. Therefore, a public enlightened as to the risks and benefits associated with technology is essential to social progress.

To convey the essence of engineering to young people, a teacher must stimulate their curiosity by describing situations that they can relate to and grasp readily. For example, one can look at a bicycle and ask such questions as, Why is the rider able to move faster than by walking? What keeps the rider in balance? What are the forces on the frame of the bicycle, and how is the frame designed to withstand them? Or one can approach the subject of power generation by starting with the question, What is fire? One can then explore such topics as combustion (oxidation), molecules, and reactions; energy transformations and the generation of heat; matter, its phases, and the production of steam; mechanical energy; turbines; and electricity and generators. The same awareness of fluid mechanics, heat transfer, diffusion, and phase transformation can be imparted to students simply by focusing on the process of cooking. And one can explore the ways in which an airplane remains airborne and thereby introduce students to aerodynamics, form, and the parameters available to the aircraft designer. Or one can focus on structures, such as bridges, and thereby delve into the relation between form and function (a subject that can also be dealt with in terms of, say, the shape of aircraft or automobiles).

When this approach is used to expose students to engineering, science can be introduced in the classroom in a natural way, and students have an opportunity to gain a practical appreciation of the power of disciplined analytical and creative thought. Moreover, the teacher can introduce in a relevant manner such important concepts as conservation; feedback; stability; equilibrium; rate phenomena (that is, the processes modeled by this simple relationship: rate equals driving force divided by resistance); approximation, estimation, and orders of magnitude; accuracy and precision; experimentation; scaling; interfacial phenomena; continuous and batch processes; cascades; system pathology (corrosion, wear, fatigue, etc.); and human/machine interactions.

Key Concepts

- *A Key Ingredient of the Engineering Process Is the Ability to Plan and Manage a Project*

Planning and managing involve all aspects of a project, from its conception to its completion. They include assembly and coordination, estimation of the resources needed (human and financial, as well as tools), development of schedules for the various phases of the project, disposition of the remaining resources and the waste upon completion, and provisions for maintenance and operation.

Comments: There is much that can be done in the classroom to involve students in simple examples of planning and to help them develop an attitude toward planning that can be useful in all facets of their lives. For instance, students can be asked to systematically plan fairly common projects or activities. Consider a school picnic: Who will participate? When? Where? What type of transportation will be needed? What kinds of food and drink will be served? How much food and drink will be needed per person? What games will be played? Should there be an emergency health kit? Who will be responsible for what? How will waste be disposed of? How much will each participant have to pay? What is the procedure if someone does not show up at the meeting place? What if someone forgets to bring the food, the tool, or the game he or she was supposed to bring? What if it rains (for example, who is supposed to notify whom?)? If the weather is marginal, how will a decision to cancel be reached? And so on. Through a seemingly trivial exercise such as this, students can develop not only a valuable skill but also an appreciation of the intricacies involved in more complex problems such as building a house, operating a factory, assembling an automobile, or launching a space shuttle.

- *Modeling Conceptualizes the Problem to Be Solved and the Solution Itself, Formulating Them as Much as Possible in Quantitative Terms*

Relevant Items: A model describes the behavior of a system. The form of the model may run the gamut from mathematical analysis to empirical correlations of data; it may consist of equations, graphs, charts, or numbers; and it may also consist of pictures or even a physical representation. The goal is to develop a useful representation of a real situation—a representation that can be easily manipulated.

Comments: Just as the artist (painter, photographer, sculptor, musician, or writer) attempts to represent an experience by means of a composition, the engineer uses a model to represent the performance of an artifact or the execution of a task. Students should learn to appreciate that the engineer does not just blunder into a creation, but rather uses imagination combined with a thoughtful, systematic approach to represent an artifact before building it. Therefore, students should understand how a design can be tested before being built (for example, through simulation), the differences between inherent stability and engineered stability (for example, a plane that will fly even if the pilot abandons the controls, versus a plane that requires hands-on control at all

times), and the influence on a design or process of tools and labor force skills. Students should be encouraged to find examples that reinforce this knowledge so that they can ask intelligent questions as citizens (for example, what is the importance of inherent stability in a nuclear reactor?).

- ***Every Design or System Has Constraints That Must Be Identified and Taken Into Account***

Relevant Items: Some of these constraints are natural, such as the conservation laws for mass, energy, and momentum; and rate-related processes, such as diffusion, heat transfer (conduction, convection, and radiation), electrical conductivity, and friction. Other constraints stem from limits on the availability of energy, materials, tools, and human skills. Further constraints—and ones that are increasingly important as technology becomes so powerful and pervasive—are economics, safety, biology, and health, as well as ethical, sociological, and political considerations.

Comments: Students should realize that the engineer must cope with *limits* in designing an artifact, just as there are limits to the range of our everyday actions. Part of the challenge for students in understanding engineering is to learn to find out where these limits are.

- ***Optimization Endeavors to Determine the Best Possible Solution to a Problem Under Its Relevant Constraints***

Relevant Items: The trade-offs of construction costs, efficiency, operational costs (for example, what is the lifetime cost of owning and running a refrigerator), aesthetics, resource utilization, safety, ethics, and a host of other factors.

Comments: Students need to appreciate that a problem confronted by an engineer ordinarily lends itself to more than one solution. Consideration of the relevant factors calls for enlightened judgment in espousing an optimal solution. But even enlightened judgment is not flawless (for instance, the design of a bridge that appears in any other respect to be optimal may fail to take into account the undercutting of the bridge's piers caused by an exceptionally high rate of flow in the river). Again, we see evidence of this truth also in everyday life.

- ***The Design Is the Core of the Engineering Process***

Relevant Items: The design embodies the results of the process that has evolved through the previous phases. It is, in effect, the blueprint of an actual artifact or process, which may be tangible (for example, a bridge or a refinery) or intangible (for example, a set of instructions or a computer program), and it constitutes a representation of how the goal can be achieved.

Comments: The design is the engineer's creative response to the goal of solving a problem. Since artifacts (be they structures, machines, or computer programs) will have an ever-important impact on their own lives, students should undertake some simple designs to reinforce their understanding of this process. This activity will later enable them to participate more effectively as citizens in decisions having a technological dimension, in that they will have learned to appreciate the factors governing a

specific design and to intelligently question all the steps leading to it. At the same time, it is critical that students realize the growing importance in engineering of—in addition to design—such issues as maintenance and environmental protection.

- *Each Design Has Side Effects*

Relevant Items: Examples of side effects include an internal combustion engine that pollutes the air and creates noise, a heart pacemaker that puts its user at risk in a magnetic field, a computer that may strain the user's eyes and reduce personal contact, a lead water pipe that may slowly poison the public, new roads that may aggravate rather than alleviate traffic congestion, an upholstered fabric that may pose a fire hazard, and a pesticide that may solve one problem but lead to others.

Comments: Consideration of side effects is—and will continue to be—of increasing importance and concern. In fact, progress in technology has helped identify side effects that were unanticipated when a design was created (for example, better instrumentation has made it possible to detect minute concentrations of toxic materials). Examples of side effects abound. The timely identification of the side effects of proposed technologies or technological solutions is an ever-increasing technical and societal challenge.

- *The Artifacts Created by Design Cannot Be Allowed to Perform Unassisted; They Require Operational Supervision, Maintenance, and Repair*

Relevant Items: Performance must be monitored for occurrences not anticipated in the design or beyond the capabilities of the design (for example, runaway chemical reactions, wind shear on an aircraft, and unexpected loads on a bridge). Engineered systems are also subject to wear, fatigue, and corrosion.

Comments: No design is perfect, and no artifact is immune from "illness" or "mortality," any more than any living organism is. Thus, an educated citizen must learn to be realistic in terms of what is needed to satisfactorily operate a technological artifact.

- *We Must Constantly Be Alert to the Possibility of Engineering Failure; Most Failures Occur at the Interface Between Systems; Failures Can Occur in All Systems, Even Well-Maintained and Supervised Ones*

Relevant Items: An appreciation of the nature of the interactions between the human and technological components of a system (sociotechnology); the examples of *Challenger*, Chernobyl, and *Titanic* (which all show a combination of design errors or inadequacies, and of human error in operations).

Comments: Artifacts may fail because of inadequacies or oversights in the design, because of conditions not anticipated by even the most conscientious designer, or because of improper use (it should be noted that most automobile accidents occur because of human error and not because of a failure in automotive technology). Students should be sensitized to the distinctions among these causes of failure, so as to be prepared to take intelligent action as citizens, to prevent or help prevent failures.

SECTION 7

NOTES ON LEARNING

We have already stressed how essential it is that students learn to do science by themselves. We further suggest that in helping students to develop an understanding of the physical and information sciences and of engineering, it can be very effective to use an integrative approach. For instance, a learning unit might focus on a body of water such as a river or pond. The class might begin by making an inventory of the properties of water and of inputs such as solar energy, rainfall, sediment and organic debris, plants and animals, and so forth. The class might then study processes. For example, it could deal with heat concepts to explain what it finds in measuring the temperature of the air, surface water, and bottom water over a period of time. General or master concepts such as the flow of various forms of energy and information through the system will emerge as the students attempt to understand both physical and biological phenomena (for example, questions of stability are involved in both the thermocline turnover of a pond and related ecosystem upheavals). Specific concepts such as surface tension and water acidity also have both physical and biological significance. Mathematical skills ranging from the manipulation of units of measurement to the use of the exponential function will turn out to be needed. The impact of geology and of human activities (including local and world history) on bodies of water will also become evident.

Students can be driven by their own curiosity to learn all of these things and more in an effort to understand their own experiments and observations, both in the field and in the laboratory. A number of other, wholly different subject areas will or could also become involved in the study of the pond, from language skills used to describe and explain phenomena (science relies heavily on clear explanation) to the arts (manual arts to build apparatus, and visual arts to "see" the body of water in other ways)—not to mention sports (fishing, swimming, and so on). The inquiry will sometimes lead in directions that even the teacher does not anticipate, and some questions will remain unanswered. Finally, the students may be given the engineering task of designing a modification of the pond—for example, an enlargement—in which they would take into consideration all the facts just learned and address issues such as the various impacts of the modification, costs, benefits, optimal design among several possible solutions, maintenance, and contingencies in case of failure.

Of course, not all schools have a pond nearby. The specific topics to be studies will have to be chosen by individual school systems and teachers. The phenomena discussed here are examples and are not intended necessarily to be included in any curriculum. We believe that all science teachers need to be given sufficient latitude to define and redefine appropriate phenomena as focal points for their curricula. The variety of the treatments in our examples underscores this belief.

What follows are further examples of the approach we suggest.

Fire

Simple observations and experiments can lead to the many physical concepts involving heat, energy, the organization of systems, gases, chemistry, materials, etc. The history of scientific ideas about heat and fire from the sixteenth century can be used, because that history, with all its blind alleys, provides vivid examples—often paralleled in the students' own experience—of how scientists struggle to understand nature. In this topic, there are many links with anthropology and technology, as well as home safety.

Carts and Cars

From the toy wagon to the automobile, everyday experience can be understood if—and only if—students learn basic physics combined with mathematics. From measurement and units, the subject will eventually lead to inertia and acceleration (in the language of differentials) and also electricity, the history of technology, the world energy supply system, and much else. Again, the subject lends itself also to an engineering project—the design and actual construction of a very simple car—as a powerful tool for understanding the engineering process, from concept to research to manufacture, testing, and operations.

The Sky

"Where is the sun right now?" If this question is repeatedly posed, and answered by reference to shadows, students can learn to measure time, find direction, and understand the seasons. "Where is the moon?" leads further into the calendar. The size of the earth and moon and relative distances can be estimated by using the ways of the ancient Greek scientists, for here scientific method, history, and geometry intertwine. Hipparchus' great achievements—the catalog of stars, the origin of scientific geography in his invention of the method of fixing terrestrial positions by means of circles of latitude and longitude, and his founding of trigonometry—can be used as a basis for simple studies and experiments that can give students a vivid sense of fundamentals, of creativity, and of the synergism of physics, mathematics, and astronomy. The elements of navigation can be introduced. The use of a simple spectroscope can bring in physics, while revealing the sun to be a star; it also opens up the major theme of how remote things can be studied.

The night sky can be perceived in many ways. One way worth exploring is through art (Vincent Van Gogh's *Starry Night*, etc.) and the history of mythological speculation.

Another approach is through science, and the most immediate question—"Why is the night sky black?"—plunges to the heart of cosmology. Students cannot go far with their naked eyes, but they can be given pictures from the great instruments, ask the same questions that past astronomers asked, and reach some answers.

APPENDIX

PHYSICAL AND INFORMATION SCIENCES AND ENGINEERING PANEL CONSULTANTS

Frank Aikman Associate Research Scientist, Lamont-Doherty Geological Observatory

Enrico Bonatti Senior Research Scientist, Lamont-Doherty Geological Observatory

Marvin P. Epstein Retired Associate, AT&T Bell Laboratories

Kenneth Ford Chief Executive Officer, American Institute of Physics

Cindy Lee Associate Professor of Marine Environmental Studies, State University of New York at Stony Brook

David Mog Senior Program Officer, Office of International Affairs, National Research Council

John Sanders Professor of Geology, Barnard College

John G. Truxal Distinguished Teaching Professor of Technology and Society, State University of New York at Stony Brook

Edward Wolf Professor and Head of Physics Department, Polytechnic University

NOTICE

This is one of five panel reports that have been prepared as part of the first phase of Project 2061, a long-term, multiphase undertaking of the American Association for the Advancement of Science designed to help reform science, mathematics, and technology education in the United States.

The five panel reports are:

- *Biological and Health Sciences: Report of the Project 2061 Phase I Biological and Health Sciences Panel*, by Mary Clark
- *Mathematics: Report of the Project 2061 Phase I Mathematics Panel*, by David Blackwell and Leon Henkin
- *Physical and Information Sciences and Engineering: Report of the Project 2061 Phase I Physical and Information Sciences and Engineering Panel*, by George Bugliarello
- *Social and Behavioral Sciences: Report of the Project 2061 Phase I Social and Behavioral Sciences Panel*, by Mortimer Appley and Winifred B. Maher
- *Technology: Report of the Project 2061 Phase I Technology Panel*, by James R. Johnson

In addition, there is an overview report, entitled *Science for all Americans*, which has been prepared by the AAAS Project 2061 staff in consultation with the National Council on Science and Technology Education.

For information on ordering all six reports, please contact Project 2061, the American Association for the Advancement of Science, 1333 H Street NW, Washington, D.C. 20005.